Empirical Evidence to Support Interdisciplinary Projects in Engineering Design Experiences

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Abstract*: With globalization driving many changes in engineering education, it is essential that the engineer of the future be able to work in interdisciplinary settings and transcend the narrow limits of a single discipline. The effort herein serves to provide empirical evidence in support of experiences which foster interdisciplinary thinking by means of team-based interdisciplinary design projects. Of importance is how these experiences help to make better engineers. Final year design experiences are well-known to have many benefits to students; yet, there are limited studies of students' learning outcomes during these experiences. During this effort, student and faculty surveys instruments, which included the compilation of over fifty learning outcomes (categorized as either "technical" or "personal/professional" learning outcomes), were developed and administered to 125 mechanical engineering seniors. Key findings reveal statistically significant differences in students' learning outcomes as a result of interdisciplinary versus single-disciplined design projects.*

1. Introduction

Design is widely considered to be the central or distinguishing activity of engineering. A capstone design course and project (final year design experience) not only provides a meaningful design experience for students, but also creates an opportunity for them to begin the process of becoming engineering professionals. Participation in capstone design projects deepens a student's understanding and promotes the communication and teamwork needed to solve complex problems. Also, enabling students to be part of the intellectual process instills in them a sense of fulfillment and imparts life-long benefits. In the United States, capstone design courses are also one of the most effective ways for engineering departments to facilitate to the outcomes of ABET (Accreditation Board for Engineering and Technology) criteria, which are similar to the generic attributes of a graduate according to the Engineers Australia Policy on Accreditation [Engineers Australia, 2006]. Although capstone design has great potential for bringing active learning to the undergraduate level, little is known about the student learning outcomes (what students know and are able to do, i.e. knowledge, skills, attitudes) as a result of these often year-long design projects. There are limited assessment studies that address what students learn as a result of capstone design projects.

Interdisciplinary competencies and thinking is a fundamental skill that our students should possess to meet the needs of the global engineer. Design experiences, such as final year experiences, provide a great opportunity for academics to foster interdisciplinary competencies by promoting interdisciplinary projects. A pilot survey instrument, which included the compilation of over fifty learning outcomes closely linked to the ABET criteria and other desired skills, was developed and administered to 125 mechanical engineering final year students at the end of their first semester capstone experience. Emphasis was placed on assessing knowledge and skills pertaining to but not limited to: problem-solving, writing and communication skills, understanding and applying knowledge, teamwork, confidence gains, organization and management skills, and interest and engagement of project. In accompaniment to the student survey intended to assess the extent to which these students are achieving certain learning outcomes, a similar faculty survey instrument was also developed to assess the extent to which faculty expected the students to meet these learning outcomes.

Overall, key findings reveal strong correlation between the student and faculty ratings as well as statistically significant differences in students' learning outcomes as a result of interdisciplinary versus single-disciplined design projects.

2. Background and Methodology

In this section, the methodology of developing the assessment instrument is addressed as well as background details about student population demographics and some general information about the senior design teams are presented.

2.1 Development of Assessment Instrument

According to ABET, students must be prepared for engineering practice through the curriculum culminating in a major design experience (most often in the senior year) based on the knowledge and skills acquired in earlier course work and incorporating appropriate engineering standards and multiple realistic constraints [ABET 2005-2006]. Thus, guiding this research assessment effort and the development of the piloting instrument was ABET's criteria "3a through k" which are listed in Table 1 as outcomes (a) through (k). Moreover, according to a recent National Academy of Engineering CASEE (Center for the Advancement and Scholarship of Engineering Education) report, rigorous literature search revealed that the engineering education community desires four additional student outcomes [Bjorklund and Fortenberry, 2005]. Based on this report, an engineering graduate should also be able to demonstrate four additional qualities which are also listed in Table 1 as outcomes (l) through (o).

Based on these fifteen learning outcomes, review of the literature and ABET-related sources, we developed a survey instrument for the students which included (a) about thirty technical learning outcomes closely linked to the ABET criteria, (b) roughly twenty personal and professional learning outcomes pertaining to knowledge, skills, and dispositional gains, (c) several qualitative-based questions about the strengths and weaknesses of the capstone design experience, and (d) general questions about the team, demographics, etc. In this survey instrument, most of the questions were based on the Likert Scaling. More specifically, in assessing the fifty learning outcomes (thirty "technical" and twenty "personal and professional"), the students were asked "how helpful was your senior design project/experience this semester in enabling you to achieve the following skills." These learning outcomes were based on a scale of one (1-Very Unhelpful) to five (5-Very Helpful), as well as having the option to select "I already had this skill." Moreover, a similar instrument was prepared for the faculty advisors to assess students' learning outcomes. They were asked "how helpful was the senior design project/experience in enabling your students to achieve the following skills".

2.2 Student Demographics

Being the seventh largest mechanical engineering department in the United States, in terms of the number of Bachelor's graduates each year, the department offers a wide-range of capstone design projects. During the current academic year of 2006-2007, the graduating class is about 275 students and the number of capstone design teams totals to over thirty-five. The capstone design projects in the department vary from automotive (such as hybrid electric vehicles, all-terrain Mini Baja, SAE race car) to robotics, fuel cells, and biomedical engineering (such as design of bioreactors, acoustic sensors for biological applications, stents). The total number of participants in this study was 125 students of whom 83% were male students and 17% female. Moreover, the 125 participants of this study corresponded to eleven design teams, which have been categorized as automotive, biomedical, robotics, renewable energy, or education (design of experiments for K-12 education efforts). The two largest groups are the automotive and biomedical design team categories, which account for 50% and 20% of the student participants respectively. Moreover, there were eleven faculty, one from each of the eleven design teams that participated in this study. The lead author served as faculty advisor to four of these design teams (corresponding to twenty-five students) pertaining to biomedical engineering design projects.

2.3 General Details about Design Teams

In better evaluating the students' learning outcomes, it is essential to gather and have a good basis of their team environment and work ethic. Overall, the design teams varied in size, there were teams as small as four and teams as large as twenty-seven. The number of faculty advisors also varied from one to three per team. In at least one-quarter of the teams, there were graduate students involved as well. Moreover, the time spent on the project per week varied from two to thirty-two hours, where the average time students spent on their design project was about 10.7 hours/week. The average time the students spent with their faculty advisor(s) averaged about 2.3 hours per week. It appears that students were overall satisfied with the amount of time they spent with their advisors, considering that the average time they would prefer to spend was about 2.5 hours per week (only 12 minutes more than the time they spent with the faculty already). Lastly, when the students were asked to rate how challenging their design project was, ratings ranged from 3 to 10 and the average rating was 8.1 (with 10 being the most challenging).

3 Results and Discussion

In assessing the fifty learning outcomes included in the survey instrument (thirty "technical" and twenty "personal and professional"), not only are results pertaining to all 125 participants presented in this section, but also how interdisciplinarity of teams affects students' learning outcomes. In a recent publication, we also assessed the effect of male and female students' learning outcomes during design experiences [Pierrakos et al., 2007].

3.1 Comparing Student and Faculty Ratings

The fifty learning outcomes assessed were categorized and linked directly to one of the fifteen (a through o) outcomes listed above, including a miscellaneous category (p) corresponding to professional learning outcomes. Table 1 lists these learning outcomes (a through o), which are accompanied by the mean student and faculty ratings, as well as the percent difference. Please note that these mean ratings (in Table 1) correspond to mean ratings for a number of outcomes relating to each of the sixteen listed. In comparing the average student and faculty ratings for the outcomes in Table 1, we observe that the biggest discrepancies (which are also statistically significant) pertain to the value the students place on the diversity of the team leading to diverse talents and ways of thinking (-5.8%, $p<0.01$), a strong work ethic (5.7%, $p<0.01$), and understanding professional and ethical responsibility (-7.9%, $p< 0.01$). Apart from these three, the remaining outcomes revealed good correlation between the student and faculty ratings. Moreover, overall for the twenty personal and professional outcomes that were assessed, the average student rating was 4.11 whereas the average faculty rating was 4.27 (4% difference), resulting to a p-value of 0.052 (barely statistically significant). For the thirty technical learning outcomes, the average student rating was 4.04 and faculty rating a 4.07 (less than 1% difference and p-value of 0.36). Thus, we can conclude that there was good correlation between the student and faculty ratings and that the students' self-assessment of their learning gains reveals a good and accurate indication of their learning.

It is also important to observe the highest and lowest rated learning outcomes. In Table 1, we observe that the highest rated outcome by the students was "an ability to function on multidisciplinary teams" (4.41), followed by "an ability to communicate effectively" (4.37), "an ability to apply knowledge of mathematics, science, and engineering" (4.24), and "an ability to design a system, component, or process to meet desired needs" (4.24). The learning outcome least rated by the students was having "an understanding of professional and ethical responsibility" (3.75). The reason for this may be that the students did not feel they achieved this outcome, illustrating that this outcome needs to be better addressed in the future.

Table 1: List of ABET criteria and additional learning outcomes, correlated with the fifty learning outcomes assessed in the survey instrument, and the corresponding mean student and faculty ratings [* p<0.05].

	ABET criteria Learning Outcomes and Skills	Student Rating	Faculty Rating	% Diff
a	an ability to apply knowledge of mathematics, science, and engineering	4.24	4.10	-3.3%
b	an ability to design and conduct experiments, as well as to analyze and interpret data	3.95	3.85	-2.6%
c	an ability to design a system, component, or process to meet desired needs	4.24	4.53	2.6%
d	an ability to function on multidisciplinary teams	4.41	4.46	1.2%
e	an ability to identify, formulate, and solve engineering problems	4.05	4.18	2.8%
f	an understanding of professional and ethical responsibility,	3.75	3.20	-7.9% *
g	an ability to communicate effectively	4.37	4.70	2.7%
h	the broad education necessary to understand the impact of engineering solutions in a global and societal context	3.99	4.00	0.2%
i	a recognition of the need for, and ability to engage in, lifelong learning	4.15	3.84	-1.8%
k	an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice	4.11	4.33	0.9%
l	an ability to manage a project, including a familiarity with business, market-related, and financial matters	4.01	4.13	-1.1%
m	a multidisciplinary systems perspective	4.10	4.13	-2.6%
n	an understanding of and appreciation for the diversity of students, faculty, staff, colleagues, and customers	4.10	4.28	-5.8% *
o	a strong work ethic	3.98	4.33	5.7% *
p	miscellaneous; personal and professional outcomes	3.89	4.29	3.2%

3.2 Effect of Interdisciplinarity of Teams

An important team characteristic that we observed to influence students' learning outcomes pertained to the interdisciplinarity and multidisciplinarity on the project. Because it is not trivial to define the nature and level of interdisciplinarity of a project or team, it was decided to choose two groups that we felt safe in categorizing as interdisciplinary and single disciplined. Considering that students in the biomedical teams, which account for 20% of the participants, had to learn new knowledge such as physiology, biology, and biomedical engineering, as well as consult with physicians and medical researchers to define their problem, these set of projects were categorized as the interdisciplinary projects. In selecting the single-disciplined projects, the automotive (AUTO) teams which accounted for 50% of the participants were chosen since these projects were within the expertise area of the students and academics, as the teams comprised of mechanical engineers mainly. It is important to also note that the BME and AUTO projects revealed a similar percentage of female and male students distributed in these teams.

Although not shown herein, the top four ranking personal and professional outcomes, which were common to both BME and AUTO groups, pertained to conveying ideas verbally, communication skills, taking initiative of the project, and valuing students teaching and learning from each other. The only difference was that the BME students rated these skills/outcomes higher than the AUTO students. Moreover, as shown in Table 2, three of these top four outcomes were found to have statistically significant differences in the rating between the two groups. Overall, for the twenty professional outcomes, the average rating by the BME students was a 4.36 and for the AUTO students a 4.10 (6% difference, $p < 0.01$).

Table 2: List of "personal and professional" learning outcomes shown to have a statistically significant difference between the biomedical (BME) and automotive (AUTO) related teams. Ranked based on lowest to highest p-value [* $p < 0.05$ and ** $p < 0.01$].

Personal and Professional Learning Outcomes Statistically Significant Between the BME and Auto Teams	BME	AUTO	% Diff
1. Taking initiative and ownership of senior design project	4.71	4.24	-11.1% **
2. Recognize intrinsic interest in learning/intellectual curiosity	4.54	4.07	-11.6% **
3. Reach beyond yourself	4.54	4.00	-13.5% **
4. Convey ideas verbally and in formal presentations	4.88	4.58	-6.5% **
5. Operate in the unknown (open-ended problems)	4.58	4.12	-11.2% **
6. Increase self-confidence	4.41	3.89	-13.3% **
7. Communicate effectively with others	4.82	4.57	-5.4% *
8. Improve work ethic	4.35	3.98	-9.2% *

Unlike the ranking of the professional outcomes which was quite similar for the two groups, the ranking of the technical outcomes was completely different. In fact, the overall mean rating for the technical outcomes was 4.20 for the BME students and 4.06 for the AUTO students (3.7% difference, $p < 0.05$). Emphasizing these differences even more, Table 3 shows that seventeen of the thirty (57%) technical learning outcomes, most of which are rated higher by the BME students, show a statistically significant rating between the two groups. From these seventeen outcomes, just four of them were rated higher by the AUTO students and pertain to using evidence to draw conclusions, recognizing knowledge transfer between project and classroom, generating multiple design concepts, and following a timeline. Some of the most pronounced differences, rated higher by the BME students, pertain to formulating a range of solutions, recognizing the need to for lifelong learning, creating a budget, conducting an experiment, etc. The BME students seemed to also better recognize and understand the ethical issues of their design/solution as well as the impact of their design/solution in a societal and global context. Overall, we can conclude that although the interdisciplinary nature of a project has some affect on students' personal and professional learning outcomes, the pronounced impact is made on their technical learning outcomes.

3.3 Summary of Overall Assessment Results

Overall, students highly valued the capstone design experience (Table 4). When students were asked if the design experience was a valuable learning event, most of the students agreed. From Table 4, we observe some trends when comparing the BME and AUTO student groups. As was the case in previous results, BME students rated the experience higher, in terms of the value of the design process, motivation for learning as well as optimism about the future, compared to the other groups.

Table 3: List of "technical" learning outcomes shown to have a statistically significant difference between the biomedical (BME) and automotive (AUTO) project teams. Ranked based on lowest to highest p-value [* p < 0.05 and ** p < 0.01].

Technical Learning Outcomes Statistically Significant Between the Biomedical and Automotive Teams	BME	AUTO	% Diff
1. Formulate a range of solutions to your engineering design problem	4.87	4.16	-17.2% **
2. Recognize the need for life-long learning	4.79	3.98	-20.3% **
3. Create a budget when managing a project	4.54	3.62	-25.6% **
4. Conduct (or simulate) an experiment	4.38	3.62	-20.8% **
5. Use evidence to draw conclusions or make recommendations	3.48	4.39	20.8% **
6. Recognize knowledge transfer between senior design project and engineering courses (classroom)	3.41	4.12	17.2% **
7. Generate multiple design concept alternatives	3.59	4.28	16.2% **
8. Use and reference engineering and scientific textbooks, journal papers, and other documents	4.50	3.97	-13.5% **
9. Recognize connections between/within engineering disciplines	4.42	3.98	-10.9% **
10. Follow a timeline when managing a project	3.52	4.10	14.1% **
11. Identify potential ethical issues and dilemmas in your design project	4.13	3.63	-13.7% **
12. Identify and establish design requirements and constraints	4.54	4.23	-7.4% *
13. Understand the ethical responsibility associated with the engineering profession and also your design project	4.17	3.81	-9.4% *
14. Utilization of modern engineering and computer tools	4.42	4.07	-8.5% *
15. Apply basic scientific and engineering principles to analyze the performance of processes and systems	4.54	4.23	-7.3% *
16. Understand the impact of your engineering design/solution in a societal and global context	4.21	3.88	-8.4% *
17. Apply engineering tools (e.g., software, lathes, oscilloscopes) in engineering practice	4.54	4.24	-7.1% *

Table 4: Summary of average ratings for the overall value of the capstone design experience.

Overall Value of Capstone Design Experience	Overall	BME	Auto
1. Overall, I am satisfied with my senior design project/experience	4.32	4.6	4.3
2. Overall, the senior design experience is a valuable learning experience	4.54	4.7	4.6
3. This semester's design project has given me a clear picture of the relevance of the engineering design process	4.12	4.5	4.1
4. This senior design experience has provided me with a new motivation for learning	3.84	4.4	3.7
5. Because of this senior design experience, I am more optimistic about my future	3.72	4.4	3.7

4 Conclusion

In this paper, quantitative assessment data pertinent to the learning outcomes of mechanical engineering final year students involved in their first semester of a capstone design experience have been presented. During this effort, student and faculty surveys instruments, which included the compilation of over fifty learning outcomes (categorized as either “technical” or “personal and professional” learning outcomes) closely linked to the ABET criteria and other desired skills, were developed. Some of the key findings of this study are addressed in the following paragraphs.

Overall, the experience was highly valued by the students. The highest three ranked personal and professional outcomes pertained to working in teams where knowledge and ideas from many engineering disciplines must be applied, communicating effectively, and valuing that students taught and learned from each other. The three highest ranked “technical learning outcomes” were being able to generate multiple design concept alternatives, recognizing the need to consult an expert, and applying basic scientific and engineering principles to analyze the performance of processes and systems. In comparing the average student and faculty ratings for the personal and professional learning outcomes, we can conclude that for about 75% of all the outcomes, there was good correlation between the student and faculty ratings.

The interdisciplinary nature of a project was an important parameter that we investigated in this study. The biomedical engineering (BME) teams were so chosen to be the projects that exemplified multidisciplinarity and interdisciplinarity, whereas the automotive (AUTO) teams were chosen to represent more of the single-disciplined projects. For both groups, the top four ranking personal and professional outcomes pertained to conveying ideas verbally, communication skills, taking initiative of the project, and valuing students teaching and learning from each other. The only difference, which turned out to be statistically significant, was that the BME students rated these skills/outcomes higher than the AUTO students. Other differences were that the BME students valued recognizing intrinsic interest in intellectual curiosity, reaching beyond self, and increasing self-confidence and work ethic, whereas the AUTO students valued working in teams, applying interpersonal skills in managing people, setting and pursuing own leaning goals, and engaging in critical self-assessment. As for the technical learning outcomes, many more pronounced differences were observed. Sixty percent of the technical learning outcomes, most of which are rated higher by the BME students, showed statistically significant differences in the rating and rank. AUTO students seemed to better value abilities pertaining to using evidence to draw conclusions, recognizing knowledge transfer between project and classroom, generating multiple design concepts, and following a timeline. On the other hand, BME students seemed to better value abilities of formulating a range of solutions, recognizing the need to for lifelong learning, creating a budget, conducting an experiment, etc. The BME students seemed to also better recognize and understand the ethical issues of their design/solution as well as the impact of their design/solution in a societal and global context. Overall, we can conclude that although the interdisciplinary nature of a project has some affect on students’ personal and professional learning outcomes, the pronounced impact is made on their technical learning outcomes/abilities.

In summary, the students highly valued the learning outcomes of the capstone experience and also were highly satisfied. Consistent for all the groups, the personal and professional skill gains are ranked higher than the technical outcomes. Lastly, some of the broader impacts of this study are that the survey instruments developed herein are as applicable and pertinent to other engineering and non-engineering students as they are to mechanical engineers. Also, this type of assessment instrument can be used not only for students participating in capstone design experiences, but also for other learning experiences, such as research, coursework and service learning.

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